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Managing Supply Chain Complexity: Foresight For Wind Turbine Composite Waste

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Abstract

The emergence of wind energy as an integral global player has witnessed a rapid growth of wind farms. While wind energy in itself is a clean energy resource, the disposal of the projected wind turbine end-of-life composite waste is likely to present a monumental management challenge that requires foresight and planning. The aim of this research was to determine the overall volume and distribution of end-of-life wind turbine composite waste and develop new metrics and mathematical tools to identify possible recycling or remanufacturing centres. Geographically distributed waste data was modelled using the centre-of-gravity method with supply chain complexity analysis utilised to develop logic for the location of recycling centres. The research predicted a total volume of over 500,000 tons of wind turbine composite waste in the UK by 2048. This paper proposes the use of new metrics to measure the complexity of waste supply chain as an evidence-based rationale for identifying appropriate sites for recycling centres. The research presents possible new approaches in waste complexity within a supply chain network to enable the development of sustainable third-party processing centres.

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Keywords: Composite Waste; Centre-of-Gravity Modelling; Supply Chain Complexity; Recycling Location

1. Introduction

As of the end of June 2016, wind turbine capacity worldwide was estimated at 500GW [1]. This represents a significant 50% increase from the total number of wind turbines installed from 2009 to 2013, and is expected to continue growing. The clean energy resource and lower amount of greenhouse gas emissions in comparison to traditional carbon-based energy sources are integral factors in the growth of wind energy technology. According to the European Wind Energy Association, wind energy fulfilled 11% of the power demand in 2016 with this share of total electricity consumption projected to reach 30% and 50% by 2030 and 2050 respectively [2]. As of early June 2017 in the UK itself, wind turbines were operating at an estimated 15,600MW capacity onshore and offshore, a volume equivalent to the power required to supply more than 10 million houses [3]. The number of wind turbines installed is likely to increase with larger rotor diameter as illustrated in Fig. 1. Earlier rotor diameter versions measured at only 15 m in 1985 but subsequently risen to 60 m in 2000 and 190 m in 2017 [4-5]. Future designs are expected to result in diameters as large as 250 m [6].

The wind turbine sector is heavily reliant on thermosetting composite materials in the production of its main turbine components. This material poses a critical challenge for future end-of-life waste management and recycling. Glass fibre reinforced polymers (GFRP) which utilises thermosetting resins are progressively used in a wide range of applications not only in renewable energy but also in transportation,

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construction and sports. The superior mechanical and physical properties make these materials very appealing [7].

The lifespan of a wind turbine is projected in various scientific studies to be in the range of 18, 20, 25, 27 [8-9] and even up to 30 years [10]. However, the 30 year projection is inconsistent with the view of wind turbine manufacturers who argue that it is not possible to extend the lifetime beyond 27 years [8]. In view of the inconsistency, this study decided to adopt the '25 years of operation to reach end-of-life' view as reasonable life for wind turbines.

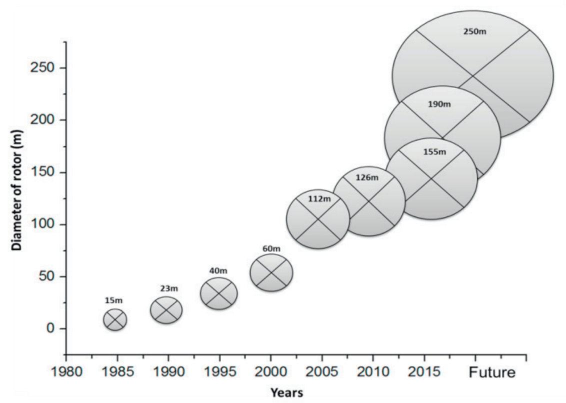

Fig. 1: The evolution of rotor size of wind turbines [4, 5]

It is predicted that 225,000 tons of expired blades would be added annually worldwide until 2034 [12] with approximately 100,000 tons on a yearly basis until 2030 in Europe alone [7]. As of the end of 2015, more than 6,037 wind turbines covering 729 individual projects were operational in the UK [11]. Wind turbines of between 1 MW to 3 MW are currently the most preferred turbine sizes for large-scale power generation while those of 100kW are more utilised for small-scale outputs [13].

The composite waste generated from wind turbines are reported in various ranges from 5.02 tons to 34.30 tons for a nominal capacity of 0.85 MW to 3.00 MW (see Table 1).

Table 1. Average composite weight for wind turbine capacities

Authors	Wind Turbine Capacity (MW)	Composite Weight (tonnes)	Composite weight average per MW (tonnes)
Welstead et al., 2013, [14]	2.00	19.80	9.90
Guezuraga et al., 2012, [15]	1.80	15.00	8.30
Guezuraga et al., 2012, [15]	2.00	34.30	17.15
Papadakis et al., 2009, [13]	1.65	16.80	10.18
Crawford, 2009, [10]	0.85	5.02	5.91
Crawford, 2009, [10]	3.00	20.07	6.69
Martínez et al., 2009, [16]	2.00	21.80	10.90
Average composite mass per MW of wind turbine			9.86

The overall average of composite weight per 2 MW output is 19.80 tons, a value closest to the estimation by Welstead et al., who projected the nominal capacity of the 2.0MW wind turbine at 19.80 tons of composite weight (i.e. consisting 17.8 tons of rotor composite and 2 tons nacelle cover composite). Drawing from this figure, it is reasonable to assume that a 1 MW wind turbine would produce 9.90 tons of composite waste [14].

An environmentally sound disposal approach is essential when dealing with end-of-life wind turbine blades. Most of the wind turbine components (i.e. tower, gearbox and generator) are recyclable or could be treated appropriately in their current form. For composite blades however, disposal becomes a critical challenge owing to the complexity of their material composition. Due to the relatively new application of composites, there is limited practical experience in recycling composites, especially in wind turbine blades. Currently, the bulk of the waste goes to landfills or is burnt at incineration plants. For the UK, 98% of composite wastes are disposed of in landfills [17].

Despite the uncertainty on the environmental profile of composite blades, recent research indicates that wind turbine blades should become a recycling priority compared to other electrical and electronic products [18]. Shuaib et al., [19] concur that composite materials have a strong recycling potential environmentally and economically. Operationally, in the UK the end-user is identified as the preferred responsible stakeholder in wind turbine take-back or end-of-life management, or to initiate recycling activities [20]. These findings provide valuable insights to drive further efforts in wind turbine blade recycling. Since a significantly growing number of wind turbines are being installed throughout the UK, the exact location, waste volume, and reverse supply chain routes are issues that merit serious deliberation.

1.1. End-of-life solutions for wind turbine blades

Wind turbines are designed with a projected lifetime of 25 years; within this period, the blades might be subjected to occasional inspection, repair and maintenance due to erosion, impact, or other possible issues. In some instances, wind turbine blades might need to be replaced with new ones due to damage [22]. Product replacement is not uncommon in the manufacturing industry and frequently takes place before parts actually reach end-of-life status.

At the commercial level, business opportunities still exist for second-hand turbine blades [23] where the component could be sold in less mature markets [1]. Innovative reuse application such as transforming dismantled wind turbines into playgrounds and children artistic centres are found in several European countries such as the Netherlands and Denmark [14, 24]. For recycling the glass fibre and carbon fibre reinforced plastic composites, there are several methods such as biotechnological, chemical, electro-chemical, fluidised bed, high voltage fragmentation, mechanical, microwave pyrolysis and pyrolysis. These technologies could be applied to wind turbines if the blades are down-sized before recycling. Of these methods, mechanical recycling, pyrolysis and fluidised bed are currently available at commercial scale while other alternatives are under development [17]. Through recycling, end-of-life blades were turned into a type of substitute fuel and filler [14]. Prior to recycling, the blades are identified, dismantled and downsized to enable ease of transportation to processing centres.

The substantial amount of waste from the composite components of end-of-life wind turbines poses a monumental management challenge that requires considerable planning and action. Although composite recycling research is progressing especially on recycling technology and recyclates usability, inefficiencies in end-of-life collection and trends in design arguably contribute to very low recycling percentages [25]. This is a logical argument since the relative quantity of scrap available at end-of-life in long-life products affects recycling activities [26]. Identifying available waste amount and its location therefore becomes a critical aspect. Presently there is no systematic investigation of end-of-life wind turbines and reverse supply chain especially for the UK scenario. To address this gap, the reverse supply chain of composite waste is assessed in terms of the waste magnitude in the UK and the complexity of distribution in the reverse supply chain network. With the first batch of wind turbines expected to reach their expiration status in 2018, there is an urgent need to examine the issue of their end-of-life management.

2. Methodology

To address the aforementioned gap in the literature, a study was conducted to ascertain the magnitude of current and future wind turbine composite waste in the UK. This was completed from studying published records on wind farms in the UK and estimating the composite waste by taking into account the average life of the wind turbines. Then, the centre-of-gravity method was used to identify a suitable location for processing all the waste, while complexity theory was used to assess the waste collection challenges in the supply chain network. The following assumptions were made, (1) wind turbine blades can be downsized for ease of transportation, (2) the waste could be collected in a single trip (3) the distance between the recycling centre and the waste resource points for transporting waste is based on the shortest driving distance and (4) the proposed location for the recycling centre has no restriction for operational purposes. These assumptions can be refined in the future along with the modelling framework.

2.1. Data sources

The lack of comprehensive information on installed wind power capacity posed a challenge for improving recycling as the necessary data was not readily available and often difficult to collate [27]. However, raw data were obtained through partially available open access wind energy directories such as Renewables Map [28] and The Wind Power [29]. These directories became the source of critical data which were then extracted and profiled for further analysis. The required full data set were the number of wind turbine farms and their status (i.e. operating, under construction, and approved), date of go-live, date of installation, the exact location of each farm (i.e. latitude, longitude, or postcode), and individual capacity in megawatts (MW).

2.2. Waste location analysis

Due to the critical role of the waste processing centre in the recycling network, it should therefore be located in an area optimal for waste transportation purposes. In this study, the centre-of-gravity method was used to identify the ideal site for waste processing centres. In this method, a recycling centre is preferably sited in the middle of all wind farm points by considering the amount of composite waste generated by each farm. The initial approach in ascertaining the centre-of-gravity was proposed by Chase et al., [30] whereby the central location for the waste processing centre could be identified by examining latitude and longitude data and transforming these into Cartesian coordinates. Hence the centre of gravity of weighted Cartesian coordinates of X, Y, and Z was computed using equations 1, 2, and 3 respectively with the coordinate data subsequently converted to latitude and longitude for a map plot.

$$X_c = \sum_{i=1}^{j} \left[\sum_{k}^{n} x_k M_k \Big/ \sum_{k}^{n} M_k \right]_{u_i} \tag{1}$$

$$Y_c = \sum_{i=1}^{j} \left[\sum_{k}^{n} y_k M_k \Big/ \sum_{k}^{n} M_k \right]_{u_i} \tag{2}$$

$$Z_c = \sum_{i=1}^{j} \left[\sum_{k}^{n} z_k M_k \Big/ \sum_{k}^{n} M_k \right]_{u_i} \tag{3}$$

where, X_c = X-coordinate of the centre-of-gravity, Y_c = Y-coordinates of the centre-of-gravity, Z_c = Z-coordinates of the centre-of-gravity, x_k = X-coordinate of k-th location, y_k = Y-coordinate of k-th location, z_k = Z-coordinate of k-th location and M_k = weightage mass of composite wastes moved to the processing centre). The k-th of location will vary based on accumulated years of study, u_i = year of study.

2.3. New measure for Supply Chain Complexity

Supply chain complexity measures the difficulty index of waste distribution channels by considering transportation distance and the amount of generated waste in the whole supply chain network. Supply chain complexity, quantified by the parameter H, is the set of individual journeys necessary to collect waste from a location, assuming that the waste could be collected in one visit. Supply chain complexity is reasonably assumed to be dependent on the waste mass and travel distance as illustrated in Fig. 2 with the circle denoting the amount of waste in each location (M_1, M_2, M_3, M_4 and M_5) and the line being the distance travelled from the waste location to the recycling centre (D_1, D_2, D_3, D_4, and D_5).

In this study, the wind turbine farm was taken as a collection point; in the event that there were more collection points, then these would need to be treated as different circles on the analysis. Overall mathematical treatment here represents the complexity of waste collection in a supply chain network. The complexity of the supply chain is modelled by equation 4, adapted from Dahmus and Gutowski who developed a model for design complexity [31]. Dahmus and Gutowski developed a method to measure the challenges to separate the material from its constituent product based on a number of separation steps as shown in equation 7. In this research, a similar approach is used to measure the challenges of waste reverse supply chain (i.e. considering transportation distance and waste volume) at particular supply chain network between waste resource points and the recycling centre.

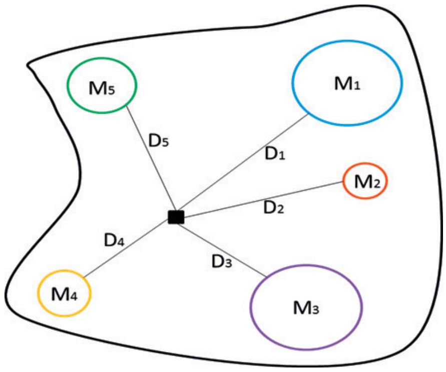

Fig. 2: Supply chain complexity assessment concept diagram

$$H_s = K\sum_{i=1}^{M} W_i D_i \log W_i D_i \quad (4)$$

where, the mass fraction W_i, of waste located at a wind farm facility, was calculated by equation 5. The journey's distance ratio from the wind farm to the identified recycling centre D_i was calculated by equation 6.

$$W_i = \frac{M_i}{M_{total}} \quad (5)$$

where W_i is the mass fraction of composites in wind turbines for a location in relation to the whole supply chain, M_i is the actual weight in kilogram (kg) of the waste and M_{total} is the total mass in kg of waste in the supply chain.

$$D_i = \frac{L_i}{R} \quad (6)$$

where D_i is the distance ratio of the waste source to the recycling centre, L_i is the item transportation distance in kilometre (km) and R is the maximum capped distance for the supply chain and in this case the longest distance across the supply chain.

3. Results

3.1. Descriptive and Statistical Analysis of Wind Turbine
3.1.1. Recent growth and future prospects

Recent available figures for the UK show a total of 532 operating wind farms between 1992 and 2016 with a further 392 approved for construction in 2017 (completion may take place until 2022) including those in various stages of building progress. The earliest commercial wind turbine data available for this study were 5 wind turbine farms commissioned in 1992. Since then, a significant growth could be seen as almost 80% additional farms were approved in addition to those initially installed and operational.

3.1.2 End-of-life of wind turbine composite waste analysis

Fig. 3 presents the cumulatively installed power capacity trend up to 2016 and a projection of future wind turbine composite waste scenario until 2048. The wind turbines installed in 1992 with 81 MW overall capacity which is expected to be discarded in 2018 will consist of 1,113 tons of composite waste. Based on the approved and under construction data from 2017 where an additional 53,428 MW capacity to be installed, a notable increase in wind turbine composite waste is predicted between 2043 to 2048.

A wind turbine farm is estimated to 'go-live' within one to five years from the approval date depending on the installed capacity. Taking the maximum years as reference, the wind turbine farms approved in 2017 will be ready to generate energy in the year 2022 before reaching their end-of-life around 2048. This batch of wind turbines was estimated to generate about 399,232 tons of composites waste. In total there will be about 528,939 tons of composites waste that ready to be managed from 2018 to 2048.

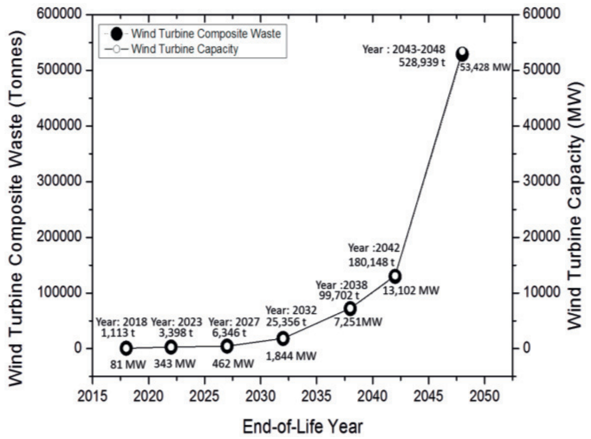

Fig. 3: The UK wind power capacity and composites waste

3.2. Centre-of-Gravity Modelling and Supply Chain Complexity Analysis

Fig. 4 shows the cumulative waste distribution for three periods (i.e. start, middle and end year of study) on a map. The red pin indicates the location of wind turbine farms while the blue location pin (M) shows the suggested centre-of-gravity location for each year. The recycling location shifts to different locations from 2018 to 2048 as a reflection of the changes in the total amount of composite waste generated and also the identified additional wind farms in operation in that particular timeframe. This presents a challenge in determining the location of recycling centres given that it might not be economically prudent to build different centres for different years, or to keep shifting locations according to waste volume and number of farms.

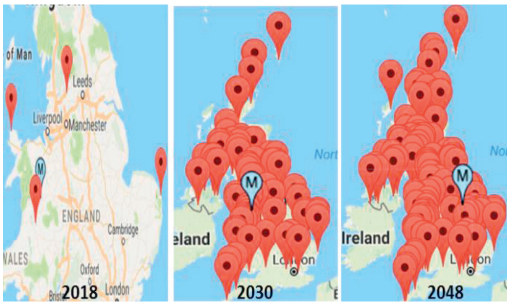

Fig. 4: Distribution of the waste location and changes in the centre-of-gravity

Supply chain complexity analysis is applied to assess the level of complexity by considering the various possible routes to recycling centres. The proposal is that by clustering waste locations, more optimal processing centres could be set up. The supply chain complexity index was assessed using equation 4 with the result indicating a reduction over the years as shown in Fig. 5 with a map illustration of those locations. The decrease in the supply chain complexity index indicates that collection for recycling in the future will potentially become easier due to the increased density of wind turbine capacity and farms.

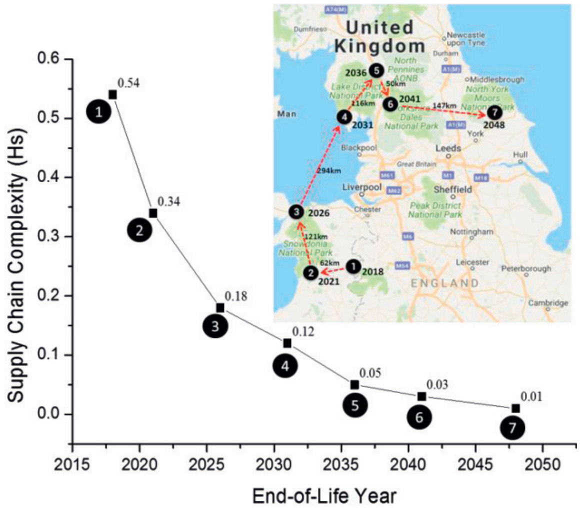

Fig. 5: Supply chain complexity and recycling centre shifts

From the graph shown in Fig. 5, a processing centre could be sited at the location predicted by the analysis indicative of a stabilisation in the complexity measure (i.e. where the rate of reduction of supply chain complexity stabilises). The location is predicted based on the data of cumulative turbine waste in 2036.

Apart from the supply chain, the complexity of wind turbine blades disassembly based on material separation theory was studied and the model is shown in equation 7.

$$H_m = K \sum_{i=1}^{M} C_i \log C_i \qquad (7)$$

Where M is the number of component materials in a mixture. C_i is the material mass fraction as defined in equation 8, and K is a constant value of -1 used to change the values into a positive index. The base of two logarithms is used to represent the binary separation applied to retrieve a material or component.

$$C_i = \frac{M_i}{M_{total}} \qquad (8)$$

Where C_i is the mass fraction of material in a part that makes a product assembly, M_i is the actual mass in kilogram (kg) of the component/material and M_{total} is the total mass of the product assembly

Fig. 6 shows the relationship between blade material separation complexity and wind turbine capacity. Based on the various wind turbine capacity ranging from 20 kW to 3000 kW, the complexity index is about 0.77 to 1.17. The complexity of the wind turbines is relatively low except for the 2MW design. This is compared to the complexity index of a mobile phone of 3.12 and DVD-R of 2.99 [18, 31]. The reduction in complexity from the 2 MW wind turbine to the newer 3 MW wind turbine is a good measure and trend for disassembly.

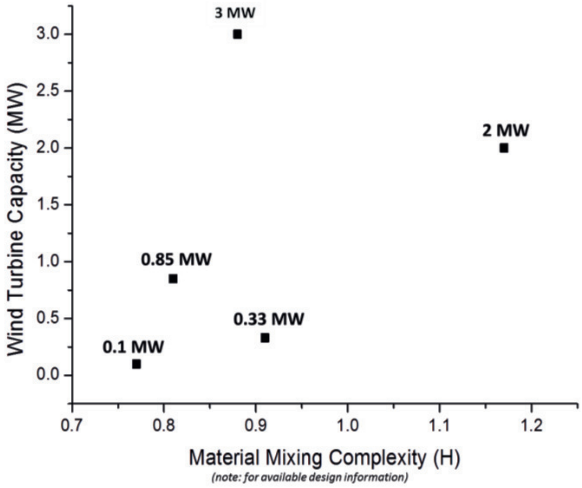

Fig. 6: Relationship of complexity and wind turbine capacities

4. Conclusion

- This paper analysed and predicted the volume of wind turbine composite waste that will be generated up to the year 2048. This was completed by using reliable and best available data from wind turbine farms in the UK.
- The result shows that more than 500,000 tons of composite waste has to be managed by 2048.
- With the first batch of commercial wind turbines expected to reach end-of-life in 2018, there is an urgent need to reconsider the facilities and planning for end-of-life waste processing centres.
- The phased installation of wind farms presents a challenge in determining the site of waste processing centres ability to fulfil present and future demands. The

volume of composite waste accumulated over time and the increase in the number of wind farms could potentially shift the centre of collection and recycling within a supply chain.

- The supply chain complexity for wind turbine waste decreases over time with a diminishing rate of change and stabilising as more waste builds up. When this rate stabilises this could be the optimum location to site recycling centres taking into consideration future wind turbines that would expire or be retired. This strategy enables better long-term planning and capturing of future needs.
- The design, technology and material of wind turbines are factors that have to be considered to facilitate end-of-life options that are higher on the waste hierarchy. Reducing design complexity and modular design would promote easier reuse, remanufacturing and recycling as well as transporting of smaller components to processing centres.
- Although wind turbine blade size and design have become larger, this has not consistently increased the complexity of material separation significantly. The major challenge for recycling is not the blade design but the location of the recycling centre.
- The reverse logistic network based on the centre-of-gravity methodology as applied in this study could provide environmentally and logistically favourable guidelines for managing wind turbine and composite waste, and enable stakeholders and third parties to make informed decisions on setting up future recycling infrastructure and facilities.
- Further work could examine the waste volumes for small to medium (sub 500 kW) wind turbines and refine the supply chain data with other new information and data sources.

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Data access

This publication used data derived from the references outlined below.

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